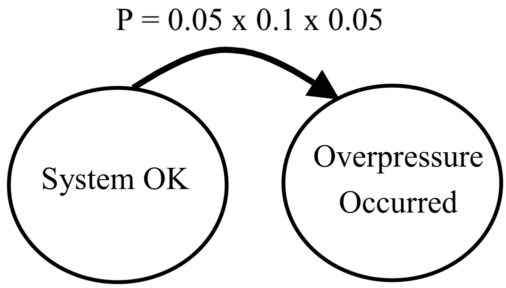
Figure 7.9 Solution to Example Using Markov Model



7.4 Summary

This chapter described some of the basic methods for likelihood analysis. These methods cover an extremely diverse range, from simple qualitative to statistical methods to fault propagation modeling. Each method has strengths and limitations so the proper method for a given situation will depend on the details of that particular case.

Statistical analysis is used to determine failure rates for a wide range of events. Failure rate data for processes and equipment is available in standard industry references. Although statistical analysis is quite appropriate for determining the failure rates of equipment items such as pumps and valves, it is not usually valid for estimating the rate at which complex systems fail. There is typically not enough operating experience or similarity between processes to make valid statistical inferences about complex systems. However, statistical modeling is useful for determining the component failure rates for the individual events or component failures that can combine and lead to full system failures. These component failure rates serve as input for the various techniques in the fault propagation family also presented here.

These fault propagation models can be extremely useful for calculating the failure rates of complex systems. Fault propagation modeling allows an analyst to determine an event rate based on the rates of initiating and contributing events and on the ways those events are logically related to the system failure in question. There are several types of fault propagation models in general use, including event trees, fault trees, reliability block diagrams, and Markov models. All are based on the idea of constructing a diagrammatic representation of the events and interconnecting logic that lead to system failure. These diagrams then allow you to apply mathematical equations to the systems to determine the ultimate failure rate or likelihood in question.

7.5 Exercises

7.1 Compare and contrast the primary methods for fault propagation modeling.

7.2 When is fault propagation modeling preferred over statistical methods for process plant failures?

7.6 References

1. American Petroleum Institute. *API Recommended Practice 752 – Management of Hazards Associated with Location of Process Plant Buildings.* Washington, DC: American Petroleum Institute, 1995.

2. Goble, William M. *Control Systems: Safety, Evaluation, and Reliability.* Research Triangle Park, NC: ISA, 1998.

3. Lees, F. P. *Loss Prevention for the Process Industries*. London: Butterworth and Heinemann, 1992.

4. Smith, D. J. *Reliability, Maintainability, and Risk.* London: Butterworth and Heinemann, 1993.

Event Tree Analysis

Event tree analysis is the most straightforward of the common fault propagation modeling techniques. This chapter describes how to use event tree analysis to both determine the frequencies of events and to average consequences where multiple outcomes are possible from a single incident. Both the physical appearance of the tree and the logical relationship between the events are explained. The basic tree begins with an initiating event that starts one or more chains of intermediate events leading to their various final outcomes. These trees will have one or more branches of multiple event possibilities that determine which outcomes can result. The outcomes are then at the end of each branch, and their frequency or probability is calculated by following the sequence set out by the branched paths that lead from the initiating event.

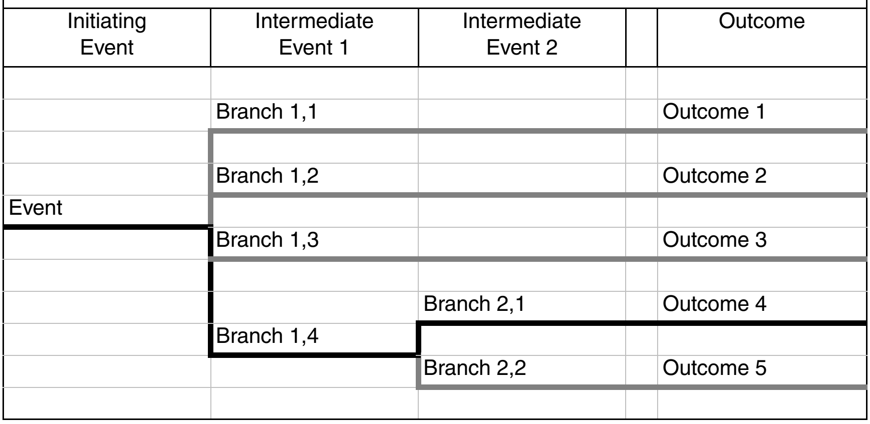
Solving for event tree outcome frequencies or probabilities is an exercise in probability math. Each individual outcome's probability or frequency is a function of the likelihood of each of the events along the path from the initiating event to that outcome. When using event trees to average outcome consequences, you must consider the probability of each branch together with its consequence. This probability acts to weight or adjust the different outcomes, which you then total to get an overall result.

8.1 Introduction to Event Tree Analysis

As we discussed in the previous chapter, event tree analysis is a form of fault propagation modeling. This particular method is well suited to estimating the risk stemming from process plant failures. Neither the initiators of industrial accidents nor the layers of protection that prevent them are typically complex, that is, they do not usually require analysis by redundant systems or the time for on-line repair. Thus, they can be accurately characterized with the probability multiplication methods that form the basis of event tree analysis. In addition, the diagrams produced during the analysis are descriptive of the scenario and clearly convey the key features, which makes this method a good way to document the risk analysis process.

A typical event tree is shown in figure 8.1. An event tree begins with a single initiating event, which is usually an action or a failure of a piece of equipment that starts the chain of events leading to one of several outcomes. The event tree's branches determine the different event sequence paths to the various outcomes. Each branch consists of a set of events that can occur in the chain leading to the final outcomes. Each branch associates a probability of occurrence with each possible event in the branch set.

Figure 8.1 Typical Event Tree



With all of these different multi-event branches, it is typical for an event tree to have multiple outcomes. The probability of each outcome is a function of the path to the outcome and the probability of each event along that path. The probability of each outcome is calculated using probability multiplication. For an outcome to occur, the initiating event must occur in combination with all of the branch events that connect the initiating event and the final outcome. The relation between the initiating events and event tree branch probabilities is a logical 'AND'. For instance, figure 8.1 shows the path to outcome 4 in bold black. In order for outcome 4 to occur, the following events must also occur: the initiating event, option 4 from the intermediate event 1 set, and option 1 from the intermediate event 2 set.

8.2 Initiating Events

An initiating event starts the chain of events that can lead to the unwanted accident if one of the protection layers does not prevent it from propagating. Any number of things can initiate an unwanted accident, from the failure of a piece of process equipment or instrumentation, such as a pump failing to provide cooling water, to the erroneous action of an operator, such as mistakenly setting the cooling water flow control set point too low. Some initiating events are not accidental. For instance, a batch process might have the potential to undergo a temperature runaway and explode. In this situation, the initiating event is the loading or mixing of the reactive materials at the beginning of the batch run.

Initiating events are usually quantified by their frequency of occurrence. For instance, a cooling water pump might fail once every 5.7 years, yielding an annual frequency of 1/5.7. Sometimes, event trees are completely described using probabilities; in these cases the initiating event will also be expressed as a probability. That probability will then be based on either a certain number of specific opportunities that the initiating event could occur or else based on a specified time period.

As we discussed in chapter 7, identifying the frequency or probability of an initiating event is a critical component of an event tree analysis. Every effort should be made to establish that value as accurately as possible using the most relevant information available.

8.3 Branches

The branches of an event tree are groups of events where different outcomes are possible depending on which event or events of the set is true. The intermediate outcome selected from each set of events that make up each branch determines the overall outcome.

Branches of event trees are usually complementary events. For instance, a branch event could be the failure of a relief valve. The event set includes two complementary events, namely: (1) relief valve fails and (2) relief valve operates. Although complementary events occur often, this is not always the case. For instance, an event tree branch might be the state of the chemical that is released, with a set of three possible states: (1) gas, (2) liquid, and (3) solid. In this case, the set of events does not even have to be mutually exclusive. If liquefied petroleum gas, or LPG, were released, the state of the release would be liquid and gas, so both of the branches would be true.

Figure 8.2 shows a branch that addresses the issue of the state of a material from a perspective other than simply its state during the release. Here, the initiating event is such that material is always released as a liquid. However, the external conditions may cause a phase change sufficient to create a flammable vapor cloud. In addition, the branch provides a choice of possible magnitudes for the release. This makes it possible to differentiate the eventual outcomes of small fires that can be readily managed with negligible consequence and large fires that require significant external assistance and can cause major harm. Figure 8.2 is clearly incomplete since at least a second set of branch events will be required to address the potential that the flammable clouds and/or liquid pools will be ignited.

Each of the events in each branch of an event tree has a probability of occurrence associated with it. When performing event tree analysis, you

Figure 8.2 Branches in an Event Tree

Initiating Event	Intermediate Event 1
	Large spill on warm surface creating flammable vapor
	Large spill on cold surface creating flammable vapor
Fuel oil spill	
	Small spill on warm surface creating flammable vapor
	Small spill on cold surface; no flammable vapor

must use probability, not frequency, in the branches. While multiplying frequency by probability yields a valid result, multiplying two frequencies together does not. If the effectiveness of a safeguard is presented in terms of failure rate, you will need to convert it into a probability over a certain reference time period or number of occasions before using it in an event tree.

8.4 Outcomes

Event tree analysis always results in multiple outcomes. Although only one outcome may be of interest, the others are also presented and can be calculated. The number of possible outcomes is a function of the number of events in each branch.

The outcomes of an event tree are typically described in terms of frequency, although under certain circumstances outcome probabilities will be desired. The outcome probability form is generated by describing the initiating event in terms of probability. Calculating the average consequence of an outcome is a good example of an occasion when event trees are quantified using probabilities instead of frequencies. We explain this instance in detail in section 8.6.

The path from an initiating event to an outcome defines the series of intermediate events that must occur for that outcome to result. It also defines the logic that must be used to show how these events are related. When following a path from the initiating event to an outcome, we relate the initiating event and branch events to the outcome by using a logical "AND." For an outcome to be true, the initiating event must be true as well as all of the branch events that lead to the outcome.

Example 8.1

Problem: Draw an event tree for getting a flat tire. Assume that the initiating event is running over a nail. Also assume that the nail may not puncture the tire, and even if the tire is punctured, it may not deflate.

Solution: The problem states that the initiating event for the tree is running over a nail. The problem also states that there are two branches for the tree. The first branch is the possibility that the nail may or may not puncture the tire. The second branch is the possibility that the tire may or may not deflate after being punctured.

When drawing the tree, the beginning point is the initiating event, usually positioned on the left. Next, from the initiating event, draw each branch. In this example there are two branch event sets. The first branch is the possibility that the nail punctures the tire. There are two possible events in this set, thus two branch paths. The second branch set is the possibility that the puncture does not cause the tire to deflate. The second branch only impacts one of the events that is possible in the first branch set, since the puncture must have occurred for this situation to be considered. The order in which the branches are shown on the tree is important in some cases, and should be considered when building an event tree.

INIT EVENT	BRANCH 1	BRANCH 2	OUTCOME
Run over	Nail punctures	Tire deflates	
nail	tire	due to puncture	
		TRUE	Tire Deflates
	TRUE		
		FALSE	Puncture, no deflation
	FALSE		No Puncture

Three outcomes are possible as a result of this initiating event: (1) the tire deflates, (2) the tire is punctured but does not deflate, and (3) the tire is not punctured.

8.5 Quantifying Event Trees

The probability or frequency of an event tree outcome is calculated as the logical combination of the events that fit together to cause the outcome. This combination includes the initiating event and the intermediate branch events in the path from the initiating event to the outcome. As stated earlier, these events are related through a logical "AND." In order for an outcome to be true, the initiating event must be true AND the first branch event must be true, and so on.

When events are related by a logical AND, the probability of the combination of events is calculated using probability multiplication. (See section 5.3.1 for more information on probability multiplication.) In other words, the outcome frequency is the initiating event frequency multiplied by the probabilities of each of the branch events on the path to the outcome.

Example 8.2

Problem: In example 8.1, an event tree diagram was built to describe the events that might result from running over a nail with a car tire. Quantify this event tree, including all possible outcomes, using the following data:

Running over a nail	once in 0.25 years
Nail punctures tire	once in 50 attempts
Punctured tire deflates	once in 5 events

Solution: Add the frequency and probability data to the event tree as shown in the following diagram. Note that the probabilities were added to both of the events in both branches. This was done by assuming that the events were complementary. Calculate the final outcome probabilities by using probability multiplication.

For the outcome of Tire Deflates calculate the frequency as follows:

$$(1/0.25) \times (1/50) \times (1/5) = 0.016 \text{ /year}$$

For the outcome of Puncture, but No Deflation, calculate the frequency as follows:

$$(1/0.25) \times (1/50) \times (4/5) = 0.064 \text{ /year}$$

For the outcome of No Puncture, calculate the frequency as follows:

$$(1/0.25) \times (49/50) = 3.92 \text{ /year}$$

INIT EVENT	BRANCH 1	BRANCH 2	OUTCOME
Run over	Nail punctures	Tire deflates	
nail	tire	due to puncture	
		1/5	0.016/yr
		TRUE	Tire Deflates
	1/50		
1/0.25 years	TRUE	4/5	0.064/yr
		FALSE	Puncture, No Deflation
	49/50		3.92/yr
	FALSE		No Puncture

8.6 Average Consequence of Incidents Using Event Trees

Event trees are used extensively to determine outcome frequencies. They are also well suited to assisting in the calculation of an average consequence. As chapter 6 demonstrated, a single incident can have multiple incident outcomes. For instance, the release of a flammable gas can result in vapor cloud explosion, flash fire, jet fire, or even have no significant impact at all. The factors that determine which outcome will occur include probability of ignition, probability of explosion, and the conditions surrounding the release. Chapter 6 also demonstrated the range of potential incident outcomes using event trees.

Each of the possible incident outcomes will have a different consequence. A flash fire will often have a much smaller consequence in terms of equipment damage than a vapor cloud explosion that has the same flammable mass and energy release potential. In addition, if no source of ignition is present in the flammable zone before the cloud disperses, the consequence may be insignificant. We can combine all of these considerations using an event tree whose outcomes are quantified in terms of probability rather than frequency.

To determine an average consequence of an incident, draw the event tree with the incident as the initiating event. Then draw the event tree with branches that will determine the various possible outcomes, such as probability of ignition. With this method, the resulting event tree outcomes will correspond to all of the potential incident outcomes. You should quantify the consequence of each of the outcomes in terms of the impact being measured. As we noted in chapters 3 and 6, these terms can include probable loss of life (PLL), probable injuries, financial loss, or any other appropriate measure of consequence.

With the average-consequence-of-incident method, the initiating event is simply quantified by stating that the incident is 100 percent likely to occur. A probability of 1 is therefore assigned to the initiating event to properly normalize the calculation. Using branch event probabilities, we can calculate the probability of each of the outcomes as for a normal event tree. We can then determine the average consequence by weighting each potential incident outcome by the probability that we calculated using the event tree, and then summing all of the contributions.

It should also be noted that when multiple incident outcomes are possible, it might be more conservative (and reduce the effort required) to use the expected maximum consequence. For instance, in example 8.3, the maximum expected consequence would be a vapor cloud explosion. A conservative consequence estimate of PLL=13.7 could have been made without going through the effort of performing the consequence modeling required for the flash fire.

Example 8.3

Problem: A release of propane can result when the packing gland of a compressor is damaged. Based on experience in this particular application, it has been determined that there is a 30 percent probability the released material will ignite. If the material does ignite, there is only a 5 percent chance an explosion will occur. Quantitative consequence analysis has determined that the following incident outcomes are possible and will have the associated consequences shown:

Vapor cloud explosion	PLL=13.7
Flash fire	PLL=8.4

What is the average consequence of a propane release from a damaged compressor packing gland?

Solution: The following graphic shows the event tree describing the potential incident outcomes. The initiating event is the release of propane, and the branches that determine the potential outcomes are probability of ignition and probability of explosion. The potential outcomes are vapor cloud explosion, flash fire, and no significant consequence. Calculate the probability of each outcome by using probability multiplication.

Once the probabilities are determined, calculate the contribution to the average from each incident outcome by multiplying each consequence by its probability. In this case, the consequence is given in terms of probable loss of life (PLL). The overall average consequence is then determined by summing the contributions from each incident outcome.

INIT EVENT	BRANCH 1	BRANCH 2	OUTCOME	PLL	CONTRIB.
Propane	Ignition	Explosion			
Release					
		5%	0.015	13.7	0.2
	30%	TRUE	VCE		
	TRUE				
1		95%	0.285	8.4	2.4
		FALSE	Flash Fire		
	70%		0.7	0	0.0
	FALSE		Nothing		
	Average Consequence in terms of PLL:				2.6

8.7 Summary

This chapter described the method of event tree analysis that is commonly used to analyze process accidents. Event tree analysis is the most straightforward of the fault propagation modeling techniques and is very powerful in situations where the series of events do not include complex redundancy or on-line repair schemes.